

Final Report

AN INVESTIGATION OF COMBUSTION INSTABILITY IN HYBRID ROCKETS

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

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March 6, 1970

AN INVESTIGATION OF COMBUSTION INSTABILITY IN HYBRID ROCKETS

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ABSTRACT

A simple analysis has been developed to describe the transition of hybrid rocket combustion from the diffusion-limited region at high pressure to the kinetic-limited domain at low pressure. Good qualitative agreement has been obtained with measured regression rate behavior in those operating regimes where surface effects such as excessive melting or charring do not occur.

PREFACE

The studies described in this report were performed principally by C. E. Wooldridge (theory) and R. J. Kier (experiments). The overall program has been under the direction of G. A. Marxman.

Administration and technical direction of the program have been under W. P. Peck, High Temperature Materials Branch, Langley Research Center.

The authors wish to acknowledge the major contributions of A. J. Amaro, R. G. McKee, Jr., W. H. Johnson, and G. R. Plapp to the experimental program. The computer calculations were the work of Miss Margery Brothers.

CONTENTS

ABSTRACT	ii
PREFACE	iii
LIST OF ILLUSTRATIONS AND TABLES	v
NOMENCLATURE	vi
I INTRODUCTION	1
II THEORETICAL STUDIES	2
III EXPERIMENTAL STUDIES	11
A. Apparatus for Regression Rate Measurements	11
B. Regression Rate Measurements	13
C. Comparison with Calculated Weight Loss Behavior	25
IV CONCLUDING REMARKS	26
APPENDIX	27
COMPUTER CODE FOR CALCULATION OF HYBRID REGRESSION RATES	28
REFERENCES	37

ILLUSTRATIONS

1	Theoretical Weight Loss as a Function of Chamber Pressure ($G_0^0 = 0.05 \text{ lb/in.}^2\text{-sec}$)	4
2	Theoretical Weight Loss as a Function of Chamber Pressure ($G_0^0 = 0.10 \text{ lb/in.}^2\text{-sec}$)	5
3	Theoretical Weight Loss as a Function of Chamber Pressure ($G_0^0 = 0.15 \text{ lb/in.}^2\text{-sec}$)	6
4	Theoretical Weight Loss of a Pure Binder Hybrid Grain as a Function of Oxidizer Mass Flux	8
5	Theoretical Weight Loss of a Hybrid Grain Containing 20 Percent Aluminum as a Function of Oxidizer Mass Flux	9
6	Theoretical Weight Loss of a Hybrid Grain Containing 40 Percent Aluminum as a Function of Oxidizer Mass Flux	10
7	Oxygen Flow Control System.	12
8	Typical Weight Loss of a Hybrid Grain as a Function of Time . .	18
9	Experimental Weight Loss of Hybrid Grains as a Function of Chamber Pressure ($G_0^0 = 0.05 \text{ lb/in.}^2\text{-sec}$)	19
10	Experimental Weight Loss of Hybrid Grains as a Function of Chamber Pressure ($G_0^0 = 0.10 \text{ lb/in.}^2\text{-sec}$)	20
11	Experimental Weight Loss of Hybrid Grains as a Function of Chamber Pressure ($G_0^0 = 0.15 \text{ lb/in.}^2\text{-sec}$)	21
12	Experimental Weight Loss of a Pure Binder Hybrid Grain as a Function of Oxidizer Mass Flux	22
13	Experimental Weight Loss of a Hybrid Grain Containing 20 Percent Aluminum as a Function of Oxidizer Mass Flux	23
14	Experimental Weight Loss of a Hybrid Grain Containing 40 Percent Aluminum as a Function of Oxidizer Mass Flux	24

TABLES

1	Experimental Data Summary	14
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NOMENCLATURE

B	Thermochemical mass transfer number
c_p	Specific heat at constant pressure
C	Constant
D_0	Initial diameter of grain
E_f	Gas-phase activation energy
G	Total mass flux
G_0^0	Oxidizer mass flux per unit area at $x = 0$ and $t = 0$
n	Order of the gas-phase reaction
L	Length of grain
p	Pressure
P_c	Chamber pressure
Q_f	Heat release per unit mass
$\dot{r}$	Regression rate
R	Gas constant
Re_x	Reynolds number based on x
t	Time
t_1	Characteristic time associated with combustion
T	Temperature; characteristic time associated with turbulent mixing
U_f	Flame temperature
U_w	Wall temperature

Subscripts

0	Conditions with zero surface mass injection; oxidizer
∞	Limiting value at high pressure

I. INTRODUCTION

Interest in the development of the hybrid rocket as an important propulsion device has naturally led to a consideration of its behavior over a wide range of operating chamber pressures. Early studies of hybrid combustion concentrated on the high-pressure regime in which the regression rate of the vaporizing surface is controlled by turbulent diffusion in the boundary layer, to the exclusion of any chemical kinetic effects.¹⁻⁶ The theory shows that in diffusion-limited combustion the regression rate is independent of pressure and depends only upon the mass flux through the port.

As the operating pressure is decreased, however, a pressure threshold is reached below which the chemical reaction time becomes significant compared to the mass diffusion time. In this regime of operation the regression rate becomes pressure-dependent at a fixed mass flux. Thus, the next step in the orderly development of hybrid combustion theory was the description of the behavior in the pressure-sensitive regime, which was carried out under a previous contract.⁷ It was found that a relatively simple analytical model based on classical turbulent flame theory exhibited good agreement with the observed regression rate/pressure dependence at a single fixed oxidizer mass flux.

The current program was designed to supplement the previous investigation by obtaining data at two other oxidizer mass flux values for comparison with analytical predictions and to investigate the growth and decay of axial traveling waves produced by injecting pressure pulses from an explosive device. Only the regression measurements were carried out before cancellation of the contract after a decision was made by NASA to terminate their hybrid combustion research contracts. The data obtained corroborated the agreement between theory and experiment noted earlier.

II. THEORETICAL STUDIES

Theoretical studies carried out up to the time of the contract cancellation were concerned with improving the predictions of the model under conditions of varying mass flux. The initial analysis⁷ gave good agreement with the regression rate/pressure behavior at constant oxidizer mass flux, but poor agreement with the regression rate/mass flux behavior at constant pressure. The problem has now been corrected by a reconsideration of the ratio of chemical reaction time to turbulent diffusion time in the boundary layer.

The regression rate $\dot{r}$ is given by the equation²

$$\frac{\dot{r}}{\dot{r}_\infty} = \left(\frac{2T}{t_1} \right)^{\frac{1}{2}} \left[1 - \frac{T}{t_1} \left(1 - e^{-t_1/T} \right) \right]^{\frac{1}{2}} \quad (1)$$

where $\dot{r}_\infty$ is the regression rate in the diffusion limit, t_1 is the characteristic chemical reaction time, and T is the characteristic turbulent diffusion time. Note that as $t_1/T \rightarrow 0$, $\dot{r}/\dot{r}_\infty \rightarrow 1$; i.e., when the reaction time is small compared to the diffusion time, the diffusion-controlled regression rate is recovered. The other limit, corresponding to $t_1/T \rightarrow \infty$, is

$$\frac{\dot{r}}{\dot{r}_\infty} = \left(\frac{2T}{t_1} \right)^{\frac{1}{2}} \quad (2)$$

In this limit, termed the kinetically controlled regime, the flame behaves as a premixed flame for which

$$\dot{r} = C_p^{n/2} U_f^{1+n/2} e^{-E_f/2RU_f} \left[1 - \frac{c_p (U_f - U_w)}{Q_f} \right]^{\frac{1}{2}} \quad (3)$$

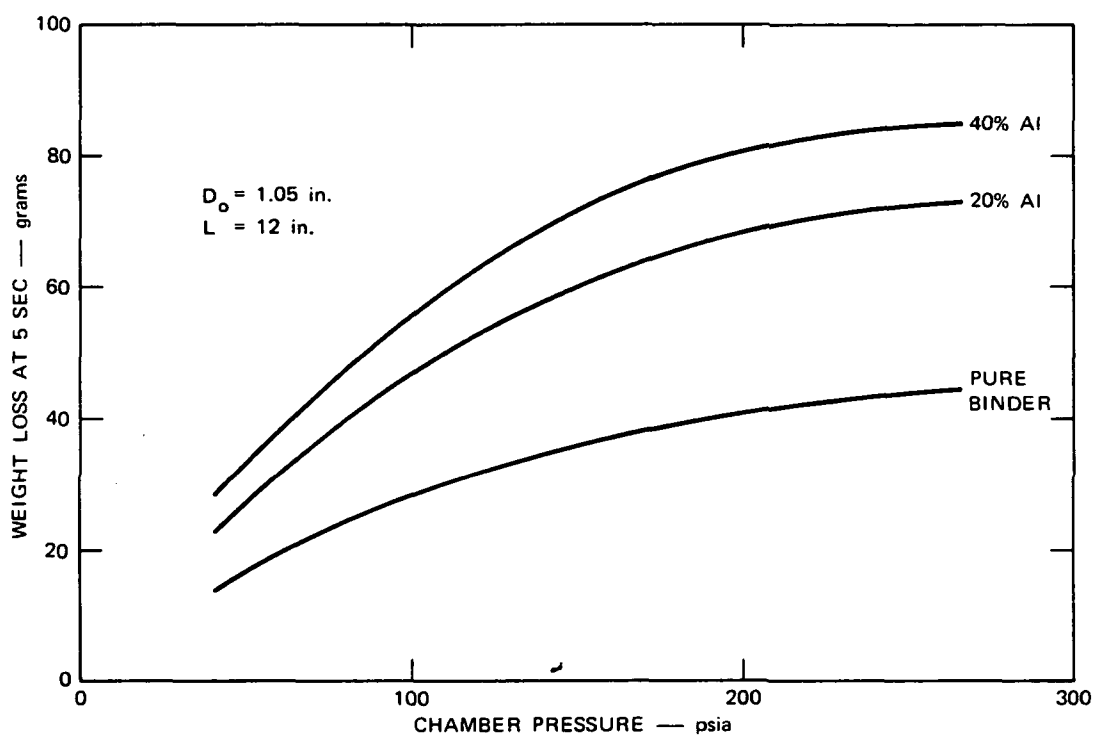
It follows then that

$$\frac{t_1}{T} = C \frac{G^2 \text{Re}_x^{-0.4} B^{0.46}}{p^n U_f^{n+2} e^{-E_f/RU_f}} \left[1 - \frac{c_p (U_f - U_w)}{Q_f} \right] \quad (4)$$

In the original formulation⁷ the quantity l_1/l_2 appeared as a multiplier on the right-hand side of the equation. The distance l_1 was the distance that the flame front propagates into unburned gas at the (kinetic) flame speed while l_2 was the characteristic scale of turbulence. In this formulation t_1/τ was found to be proportional to the square root of the expression given in Eq. 4; this gave a dependence on mass flux G that did not agree with experimentally observed behavior. Much better qualitative agreement with the trends shown by the data is now obtained, as will be discussed in the next section.

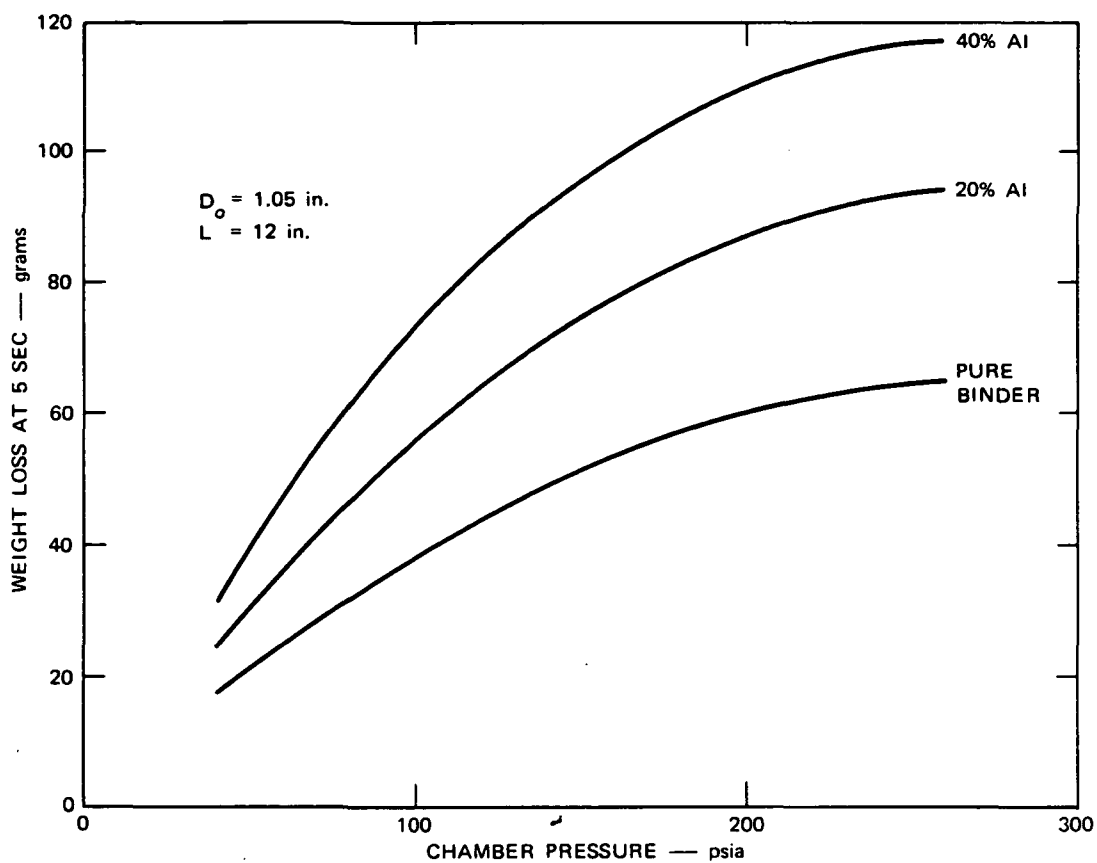
To employ Eq. 4 it is necessary to choose a value for the empirical constant C . The empiricism enters the problem through the kinetics formulation in which the functional dependence of the reaction rate, but not its absolute value, is chosen. For the present calculations the constant was evaluated by assuming that $\dot{r}/\dot{r}_\infty = 0.75$ when $p = 150$ psia and $G_0^0 = 0.05/\text{in.}^2\text{-sec.}$ These numerical choices are supported by the available experimental data that are given in the next section.

Calculations of weight loss as a function of chamber pressure for a 5-sec time interval are shown in Figs. 1 through 3. Weight loss is shown rather than regression rate because it is the measured quantity in the experiments. A print out of the computer code used for these calculations is given in the Appendix. Because the physical properties (density, heat of vaporization, flame temperature, etc.) of PU (polyurethane) and PBAN (polybutadiene-acrylic-nitrile) are nearly the same,⁷ the computed weight losses for the two binder systems differed by no more than 2% over the ranges of pressure and oxidizer mass flux considered. Therefore, there is no differentiation between the two binder systems delineated in the figures. Oxygen was considered as the oxidizer in all of the calculations.



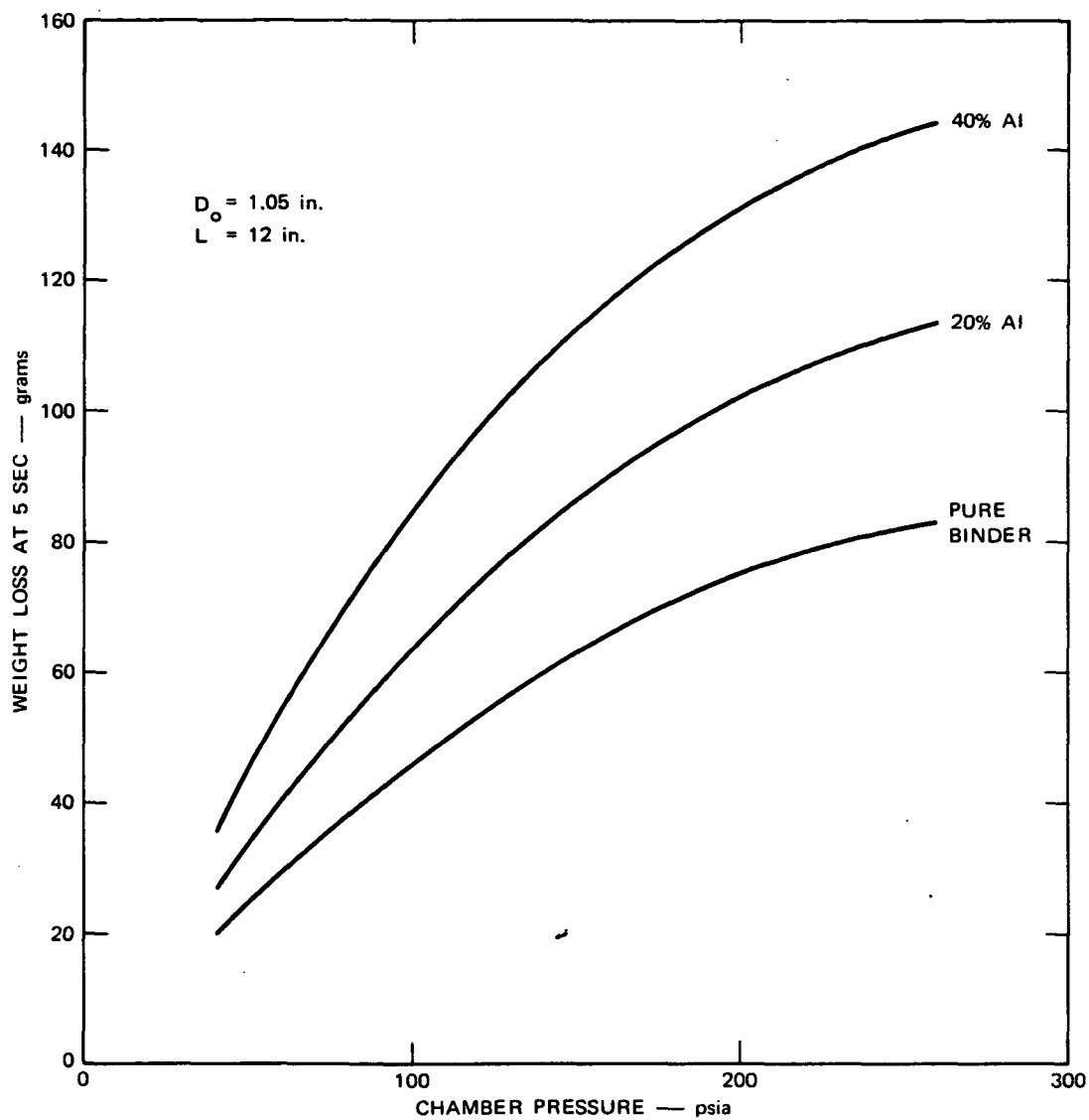
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FIGURE 1 THEORETICAL WEIGHT LOSS AS A FUNCTION OF CHAMBER PRESSURE
 ($G_o^o = 0.05 \text{ lb/in.}^2\text{-sec}$)



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FIGURE 2 THEORETICAL WEIGHT LOSS AS A FUNCTION OF CHAMBER PRESSURE
 $(G_o^o = 0.10 \text{ lb/in.}^2\text{-sec})$



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FIGURE 3 THEORETICAL WEIGHT LOSS AS A FUNCTION OF CHAMBER PRESSURE
 ($G_o^o = 0.15$ lb/in.²-sec)

Figures 1 through 3 show that the dependence of weight loss on chamber pressure at low pressures becomes more marked as the oxidizer mass flux increases. Increasing the metal loading at a fixed oxidizer mass flux also amplifies the effect, in this case because of the dependence of radiative heat transfer on pressure.

Figures 4 through 6 are cross-plots of the results shown in Figs. 1 through 3 to show the dependence of weight loss on oxidizer mass flux as a function of chamber pressure. At low chamber pressures, in the kinetically controlled regime, the weight loss is nearly independent of oxidizer mass flux. As the pressure increases the slope of the curve increases, with the proportionality approaching something less than the 0.8 power. Here the diffusion-controlled regime, in which regression rate is proportional to the 0.8 power of the total mass flux, is being approached.

The trends predicted by the theory are, of course, those that were built in through the original formulation of the physical problem. The problem was formulated on the basis of past results obtained at SRI⁷ and elsewhere.⁸⁻¹⁰ A comparison with more recent data obtained under this contract is given in the next section.

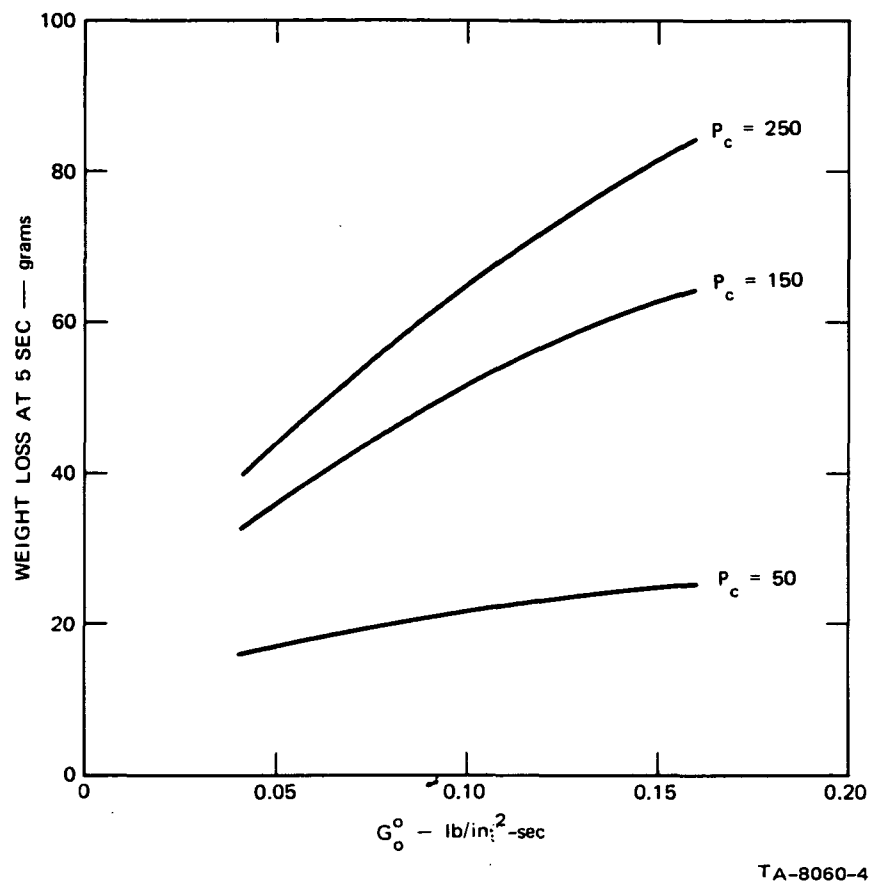
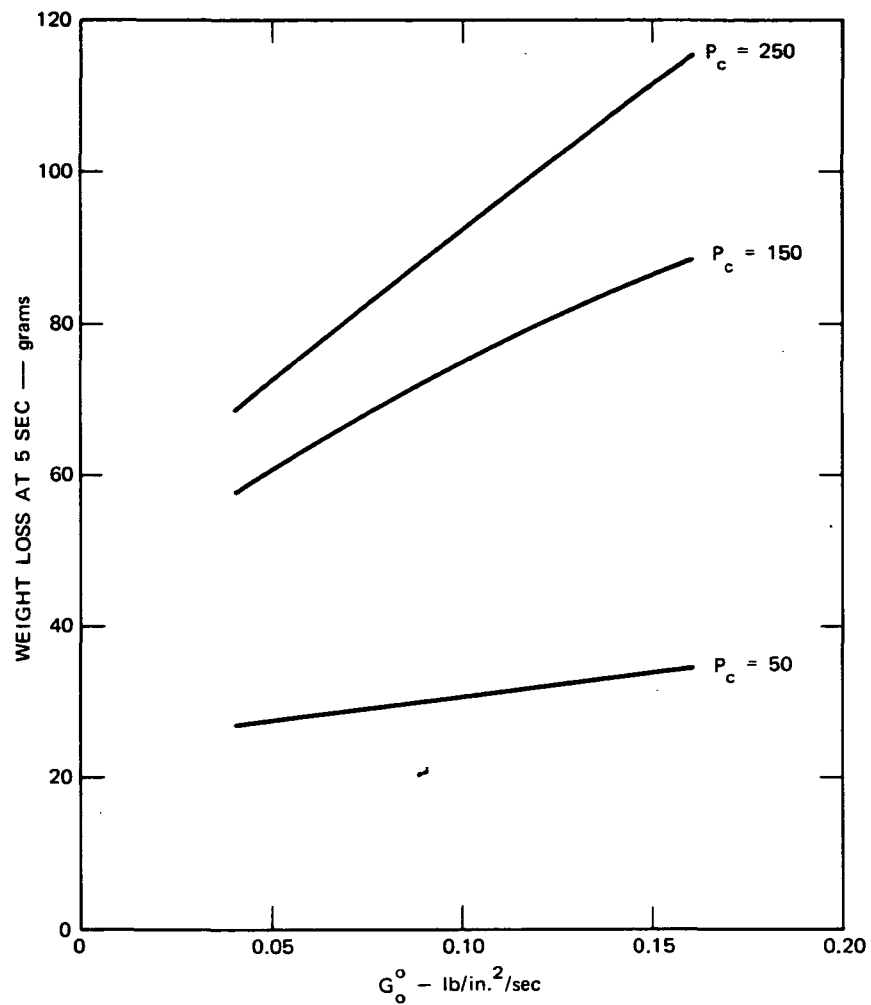
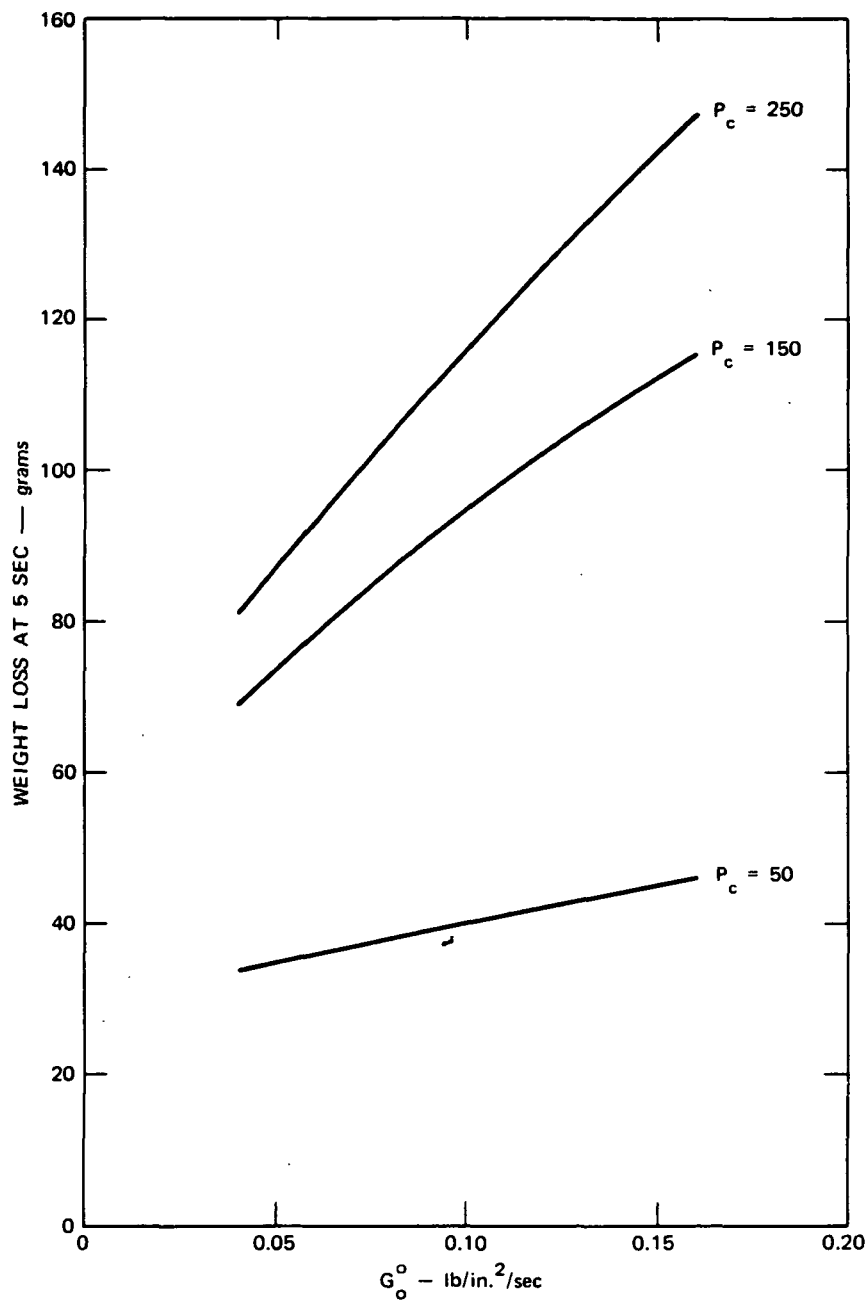


FIGURE 4 THEORETICAL WEIGHT LOSS OF A PURE BINDER HYBRID GRAIN AS A FUNCTION OF OXIDIZER MASS FLUX



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FIGURE 5 THEORETICAL WEIGHT LOSS OF A HYBRID GRAIN CONTAINING 20 PERCENT ALUMINUM AS A FUNCTION OF OXIDIZER MASS FLUX



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FIGURE 6 THEORETICAL WEIGHT LOSS OF A HYBRID GRAIN CONTAINING 40 PERCENT ALUMINUM AS A FUNCTION OF OXIDIZER MASS FLUX

III. EXPERIMENTAL STUDIES

The experimental studies were designed to provide data that would assist in the development of a theoretical model that could be used to predict the regression rate behavior and combustion instability limits for hybrid rocket motors operating in the low-pressure regime. The experiments originally proposed for this program included four types of tests:

1. Hybrid motor tests for determining the mean regression rate of various propellant systems in the pressure-sensitive regime over a range of oxidizer mass flux.
2. Hybrid motor tests in which axial instability would be induced by pressure pulses. The growth and decay of the pressure wave would be studied under varying operating conditions.
3. Slab burner tests to obtain Schlieren photographs of the relative thickness and position of the flame zone under the various operating conditions chosen.
4. Atmospheric combustion tests in the combustion simulator to determine the effect of heat release distribution on the heat transfer to the wall.

Because of the premature termination of the program only the first phase of the experimental studies was completed.

A. Apparatus for Regression Rate Measurements

The hybrid motor tests for determination of the mean regression rate utilized the existing flow facility that is shown schematically in Fig. 7. This facility was originally designed for liquid rocket engine tests with cryogenic oxidizers and was therefore constructed of 304 stainless steel with Teflon* and/or Kel-F[†] seats and seals. Sonic chokes operated above their critical pressure ratio were used to maintain a constant oxidizer mass flow throughout each test. These chokes were calibrated against a flow meter in the preceding hybrid combustion instability program (Contract No. NAS 1-7310).⁷

*Trademark, E. I. du Pont de Nemours and Co.

†Trademark, 3M Company

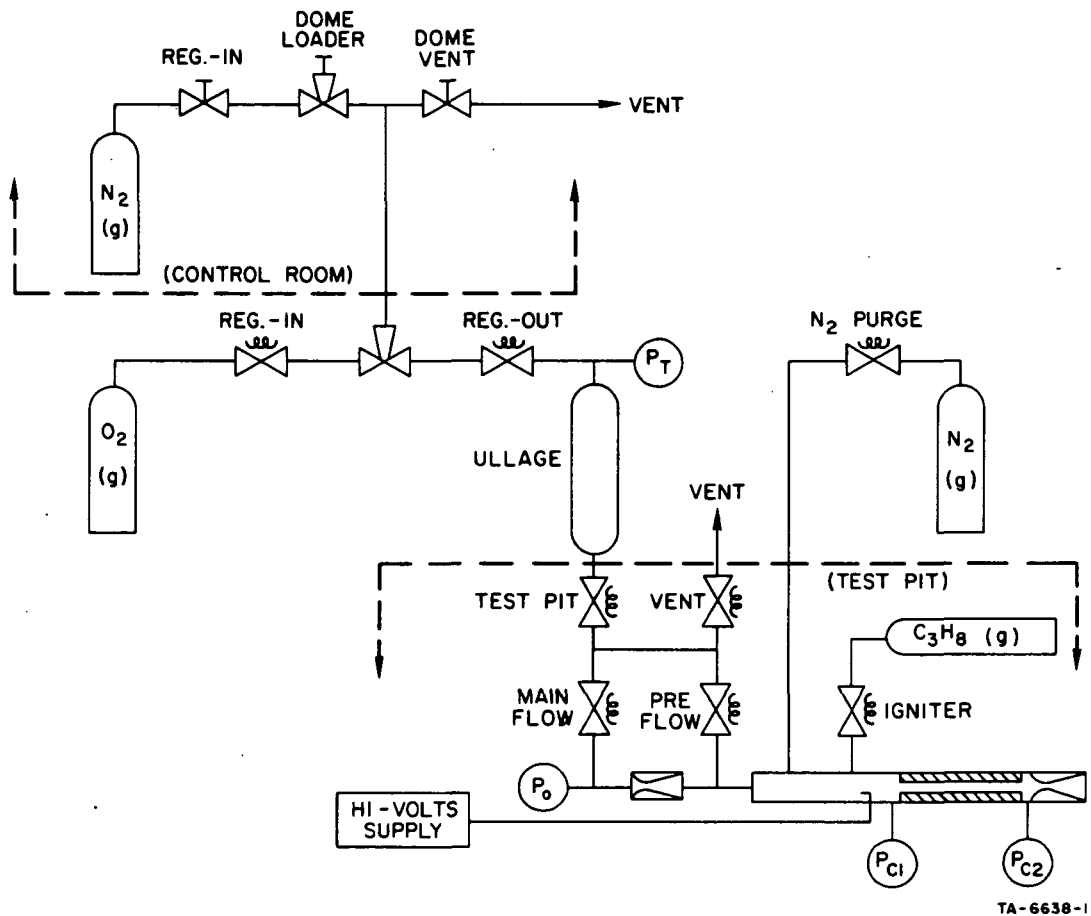


FIGURE 7 OXYGEN FLOW CONTROL SYSTEM

The motor configuration used was the same as in the prior program. The 2-1/2-inch-diameter motor consisted of a 12-inch flow-straightening section in which the ignition system was housed, a 12-inch tubular grain with a 1-inch-diameter internal perforation, and a water-cooled nozzle assembly.

The grain is ignited by preflowing a small amount of oxygen and propane into the chamber and igniting it with a spark plug. The ignition system is preset so that it operates near the lower flammability limit for the oxygen-propane mixture, thus yielding an oxygen-rich high-temperature source. The time for the flame to spread from the head end of the grain to the nozzle end was determined to be approximately 1 sec. Therefore, the main flow valve was delayed for that length of time. The weight of fuel typically consumed during this ignition process was determined to be 0.5 g which is about 1% of the amount of fuel that would be consumed in a 5-sec test at a regression rate of 0.01 in./sec.

B. Regression Rate Measurements

Weight loss data were obtained for test durations of both 5 and 10 seconds. The grains were dimensionally measured before and after each test. The data were obtained for PU and PBAN binders containing 0, 20, and 40 percent aluminum for chamber pressures ranging from 30 to 250 psia and for oxidizer mass fluxes of 0.05, 0.10, and 0.15 lb/in.²-sec. The oxidizers used for all of the tests was gaseous oxygen. The data from these tests are presented in Table I. PU and PBAN were chosen for comparative binder tests because their surface behavior during regression is quite different. PU sublimates cleanly at the regressing surface after a melt is formed, while the regression of PBAN consists of the stripping of hydrogen from the surface layer, leaving a carbonaceous char that subsequently breaks away in particulate form.

Since these two systems behave differently the weight loss data will be subsequently discussed separately for each system; however, a brief discussion of the data handling procedure is in order.

Table I

EXPERIMENTAL DATA SUMMARY

Grain Number	Binder Type	Aluminum (%)	Chamber Pressure (psia)	G_0 (lb/in. ² -sec)	Weight Loss (grams)	Run Duration (sec)
508	PU	0	34	0.05	45	5.1
509	PU	0	33	0.05	86	10.0
510	PU	0	77	0.05	58	5.0
511	PU	0	78	0.05	107	9.6
512	PU	0	165	0.05	77	5.0
513	PU	0	170	0.05	147	9.4
514	PU	0	260	0.05	79	4.0
515	PU	0	253	0.05	156	9.2
527	PU	0	75	0.10	59	5.0
528	PU	0	260	0.10	97	5.0
517	PU	0	35	0.15	60	5.0
518	PU	0	35	0.15	108	9.6
519	PU	0	80	0.15	67	5.0
521	PU	0	74	0.15	124	9.6
523	PU	0	160	0.15	87	4.9
524	PU	0	130	0.15	163	9.6
525	PU	0	225	0.15	92	4.9
526	PU	0	230	0.15	202	9.6
556	PU	20	34	0.05	49	4.7
557	PU	20	35	0.05	101	9.5
558	PU	20	72	0.05	60	5.0
559	PU	20	81	0.05	133	9.8
560	PU	20	130	0.05	82	5.0
561	PU	20	138	0.05	174	9.6
543	PU	20	36	0.10	59	5.0
544	PU	20	35	0.10	128	9.8
545	PU	20	71	0.10	84	5.0
546	PU	20	87	0.10	186	9.8
547	PU	20	156	0.10	130	5.0
548	PU	20	163	0.10	252	9.8
549	PU	20	32	0.15	65	5.2
550	PU	20	35	0.15	128	9.7
551	PU	20	62	0.15	82	5.0
552	PU	20	83	0.15	196	9.8
553	PU	20	157	0.15	139	5.1
554	PU	20	169	0.15	277	9.5

Table I (contd)

Grain Number	Binder Type	Aluminum (%)	Chamber Pressure (psia)	G_0^0 (lb/in. ² -sec)	Weight Loss (grams)	Run Duration (sec)
445	PU	40	34	0.05	51	4.8
446	PU	40	42	0.05	139	9.4
447	PU	40	103	0.05	116	4.8
448	PU	40	37	0.10	70	4.6
449	PU	40	36	0.10	141	9.6
451	PU	40	75	0.10	100	5.0
565	PU	40	65	0.10	201	9.4
452	PU	40	183	0.10	178	5.0
566	PU	40	177	0.10	174	4.8
567	PU	40	170	0.10	362	9.4
438	PU	40	35	0.15	76	4.8
439	PU	40	37	0.15	164	9.5
440	PU	40	67	0.15	97	4.8
441	PU	40	67	0.15	232	9.8
442	PU	40	153	0.15	186	5.0
443	PU	40	158	0.15	396	9.6
209	PBAN	0	32	0.05	56	5.0
211	PBAN	0	32	0.05	105	10.0
201	PBAN	0	85	0.05	74	4.0
204	PBAN	0	85	0.05	157	10.1
207	PBAN	0	160	0.05	85	5.2
208	PBAN	0	158	0.05	148	10.0
212	PBAN	0	235	0.05	75	5.1
213	PBAN	0	220	0.05	123	9.4
498	PBAN	0	32	0.10	55	5.3
505	PBAN	0	35	0.10	112	9.7
500	PBAN	0	80	0.10	84	5.4
501	PBAN	0	80	0.10	158	9.9
499	PBAN	0	170	0.10	94	5.3
504	PBAN	0	175	0.10	174	9.8
502	PBAN	0	225	0.10	92	5.2
503	PBAN	0	225	0.10	166	9.8
199	PBAN	0	31	0.15	52	4.8
200	PBAN	0	30	0.15	98	9.5
197	PBAN	0	74	0.15	75	4.8
198	PBAN	0	74	0.15	152	9.4
169	PBAN	0	157	0.15	98	5.0
192	PBAN	0	158	0.15	188	9.6

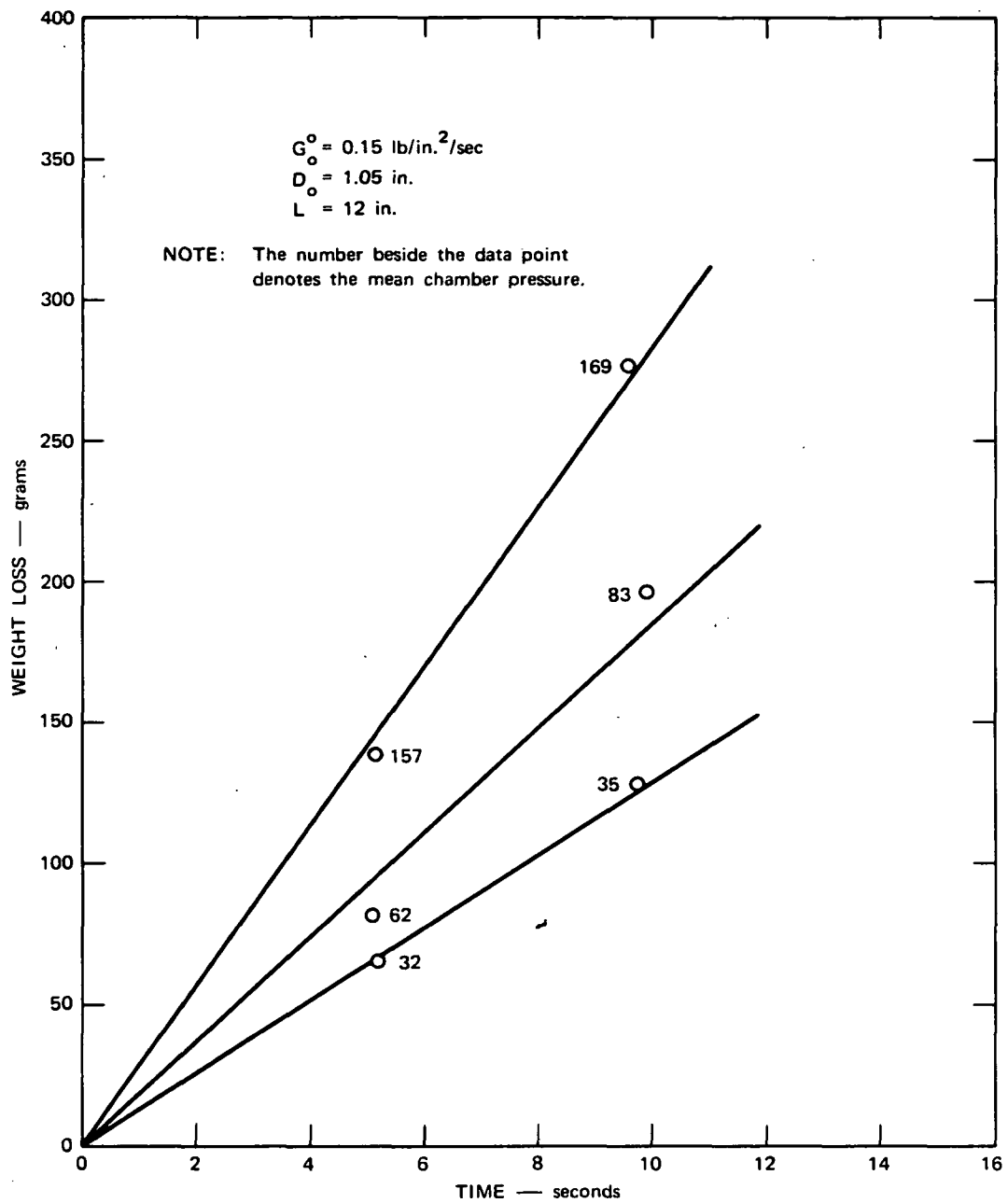
Table I (concl'd)

Grain Number	Binder Type	Aluminum (%)	Chamber Pressure (psia)	G_0^0 (lb/in. ² -sec)	Weight Loss (grams)	Run Duration (sec)
268	PBAN	20	32	0.05	70	5.1
269	PBAN	20	31	0.05	122	10.0
272	PBAN	20	75	0.05	88	5.3
273	PBAN	20	75	0.05	162	9.6
270	PBAN	20	150	0.05	101	5.2
271	PBAN	20	158	0.05	172	10.0
274	PBAN	20	220	0.05	87	5.0
275	PBAN	20	210	0.05	143	9.6
477	PBAN	20	32	0.10	56	5.2
478	PBAN	20	32	0.10	122	9.6
479	PBAN	20	77	0.10	94	5.3
480	PBAN	20	80	0.10	177	9.8
481	PBAN	20	145	0.10	108	5.3
482	PBAN	20	149	0.10	199	9.8
483	PBAN	20	230	0.10	111	5.3
484	PBAN	20	236	0.10	187	9.8
260	PBAN	20	31	0.15	65	4.9
263	PBAN	20	31	0.15	128	9.6
258	PBAN	20	67	0.15	91	4.8
259	PBAN	20	70	0.15	184	9.5
256	PBAN	20	150	0.15	119	4.8
257	PBAN	20	145	0.15	242	9.6
456	PBAN	40	30	0.05	62	5.2
457	PBAN	40	30	0.05	120	9.6
458	PBAN	40	75	0.05	95	5.2
460	PBAN	40	75	0.05	189	9.6
461	PBAN	40	150	0.05	111	4.9
462	PBAN	40	155	0.05	198	9.6
470	PBAN	40	35	0.10	74	5.2
471	PBAN	40	39	0.10	153	9.6
468	PBAN	40	78	0.10	112	5.2
469	PBAN	40	85	0.10	219	9.8
466	PBAN	40	160	0.10	132	5.2
467	PBAN	40	167	0.10	252	9.6
323	PBAN	40	30	0.15	73	4.9
324	PBAN	40	31	0.15	138	9.4
320	PBAN	40	71	0.15	100	4.9
321	PBAN	40	78	0.15	215	9.6
318	PBAN	40	147	0.15	145	4.8
319	PBAN	40	155	0.15	315	9.6

Typical weight loss data as a function of time are presented in Fig. 8. The mean chamber pressure at which the fuel is burnt is denoted beside each data point. Since minor variations in test duration did occur, the data were standardized at 5 sec. This relatively short time was chosen to minimize the effect of the change in oxidizer mass flux as the internal perforation diameter increased. The data were then plotted as a function of chamber pressure and oxidizer mass flux for the various aluminum loadings made. From the weight loss versus chamber pressure curves, constant pressure lines were constructed for the weight loss versus oxidizer mass flux curves. The chamber pressure values used are mean values. For either pure PBAN or PU the observed pressure deviation about the mean was very minor. However, in the systems that contained aluminum the deviations were much more severe because of the coating of the nozzle throat with aluminum oxide. The most severe cases were those in which the chamber pressure was high and/or the oxidizer mass flux was low; both cases necessitate small nozzle throat sizes. With this variation a precise mean value of chamber pressure for repetitive tests were difficult to obtain.

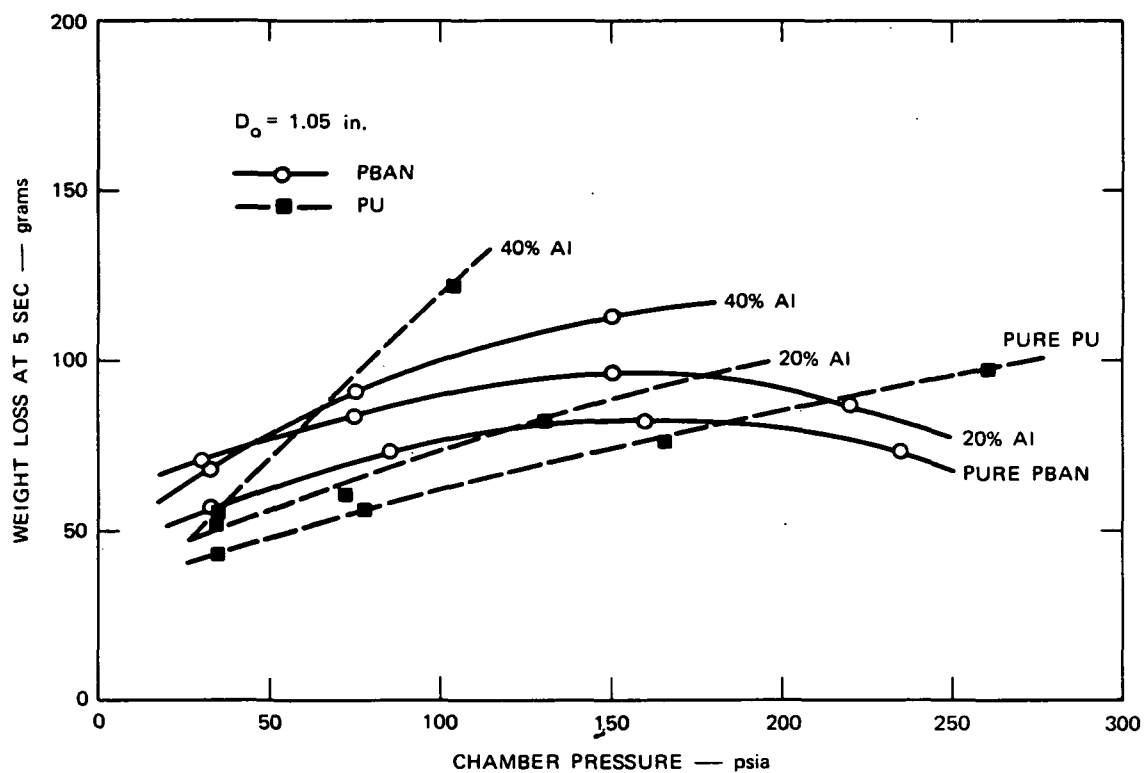
Under the current program the first data to be taken were the weight loss data at the low value of oxidizer mass flux. These data are presented in Fig. 9. Upon examining the data, it can be seen that the PBAN results fall off for chamber pressures above 150. One possible explanation is that this decline occurs when the velocity is reduced below the level required to efficiently remove the char layer that is present. This idea is supported by the results shown in Fig. 10 where the oxidizer mass flux is 0.10 lb/in.²-sec. Here the velocity is large enough to stabilize the regression rate for pressures over 150. In Fig. 11 the oxidizer mass flux is further increased and the regression rate becomes a function of chamber pressure throughout the range of test conditions.

The dependency of weight loss of the PBAN system on oxidizer mass flux is depicted in Figs. 12 through 14. At lower values of chamber pressure the regression rate is relatively independent of mass flux. However, as the chamber pressure is increased the transition from a kinetically



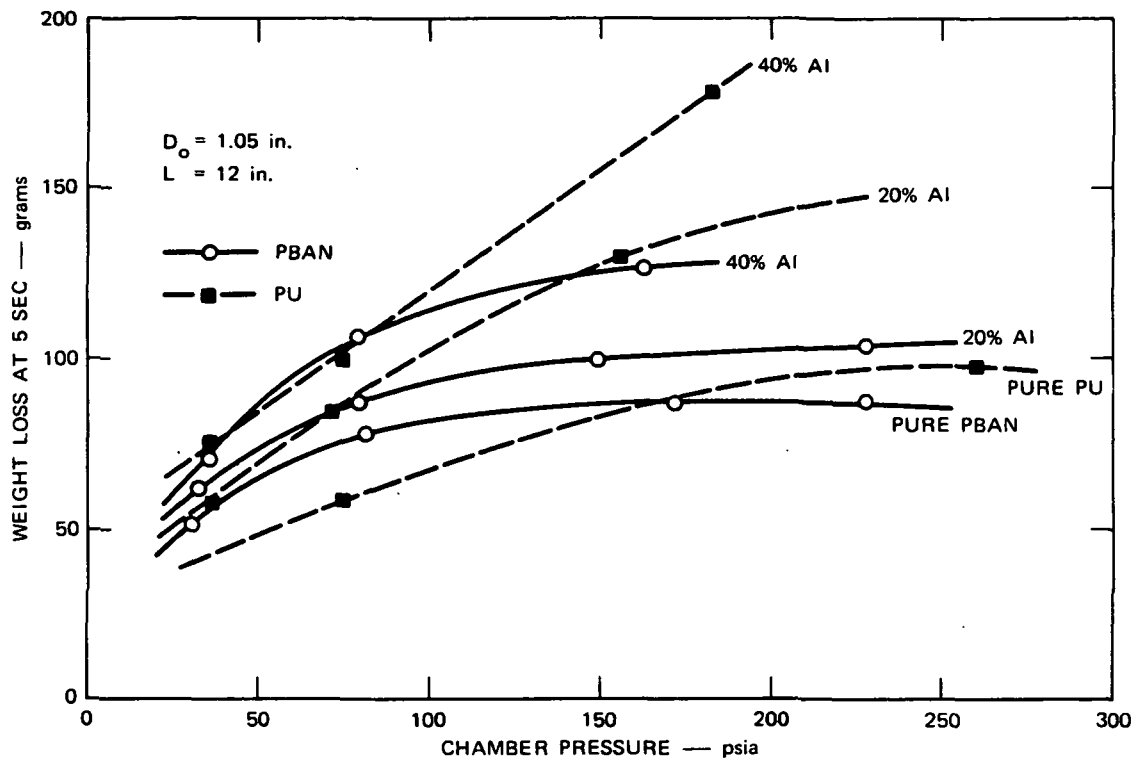
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FIGURE 8 TYPICAL WEIGHT LOSS OF A HYBRID GRAIN AS A FUNCTION OF TIME



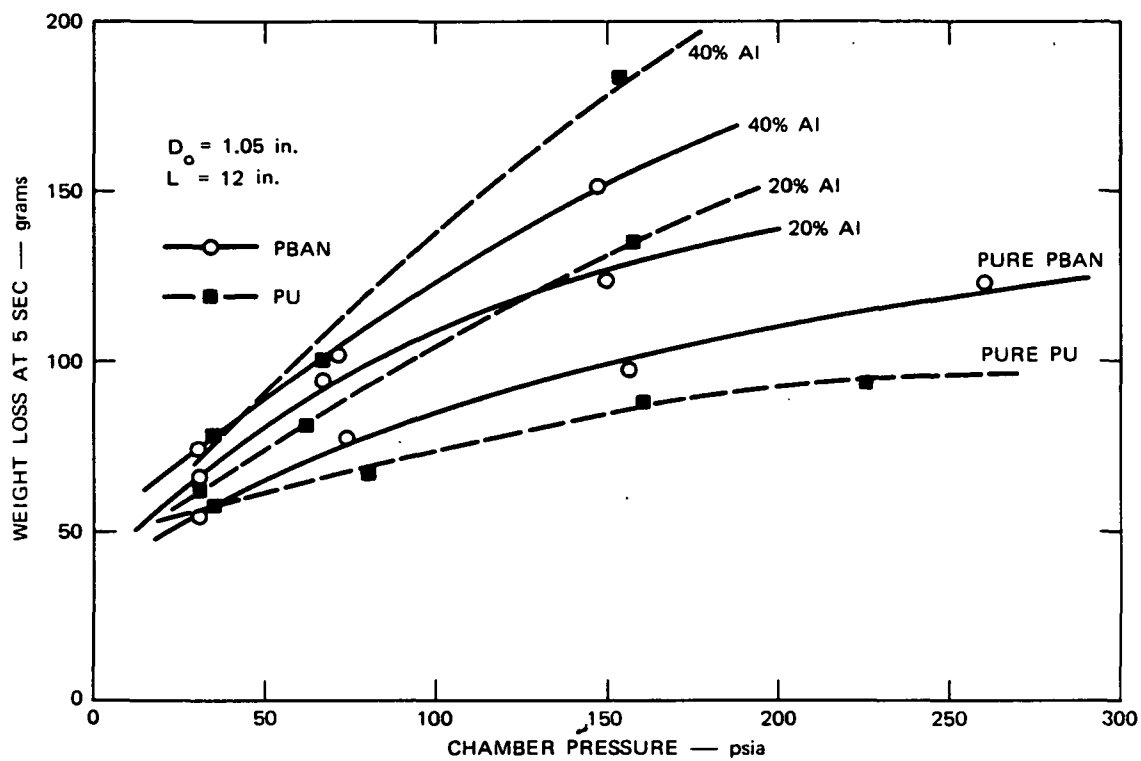
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FIGURE 9 EXPERIMENTAL WEIGHT LOSS OF HYBRID GRAINS AS A FUNCTION OF CHAMBER PRESSURE ($G_o^0 = 0.05$ lb/in.²-sec)



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FIGURE 10 EXPERIMENTAL WEIGHT LOSS OF HYBRID GRAINS AS A FUNCTION OF
 CHAMBER PRESSURE ($G_o^0 = 0.10$ lb/in.²-sec)



TA-8060-9

FIGURE 11 EXPERIMENTAL WEIGHT LOSS OF HYBRID GRAINS AS A FUNCTION OF CHAMBER PRESSURE ($G_0^0 = 0.15 \text{ lb/in.}^2\text{-sec}$)

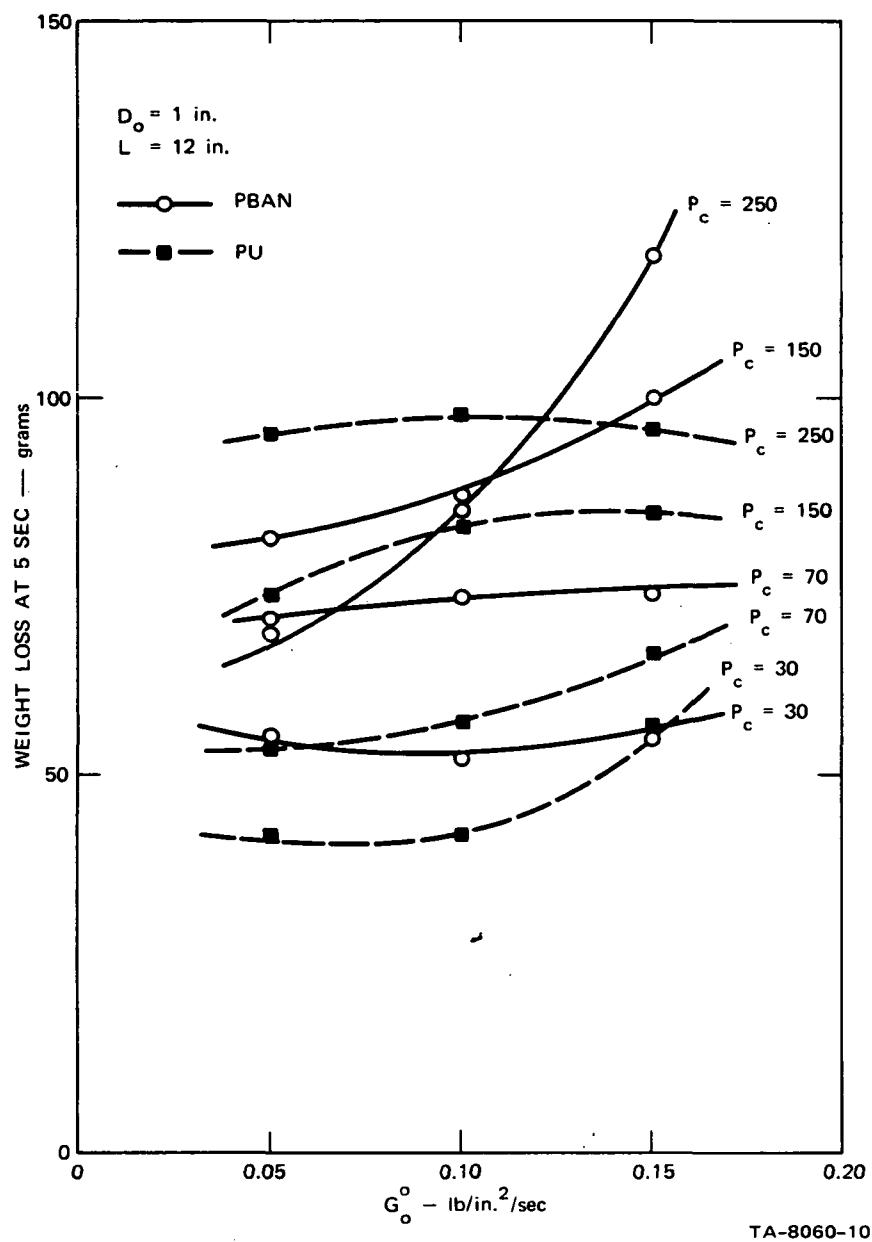


FIGURE 12 EXPERIMENTAL WEIGHT LOSS OF A PURE BINDER HYBRID GRAIN AS A FUNCTION OF OXIDIZER MASS FLUX

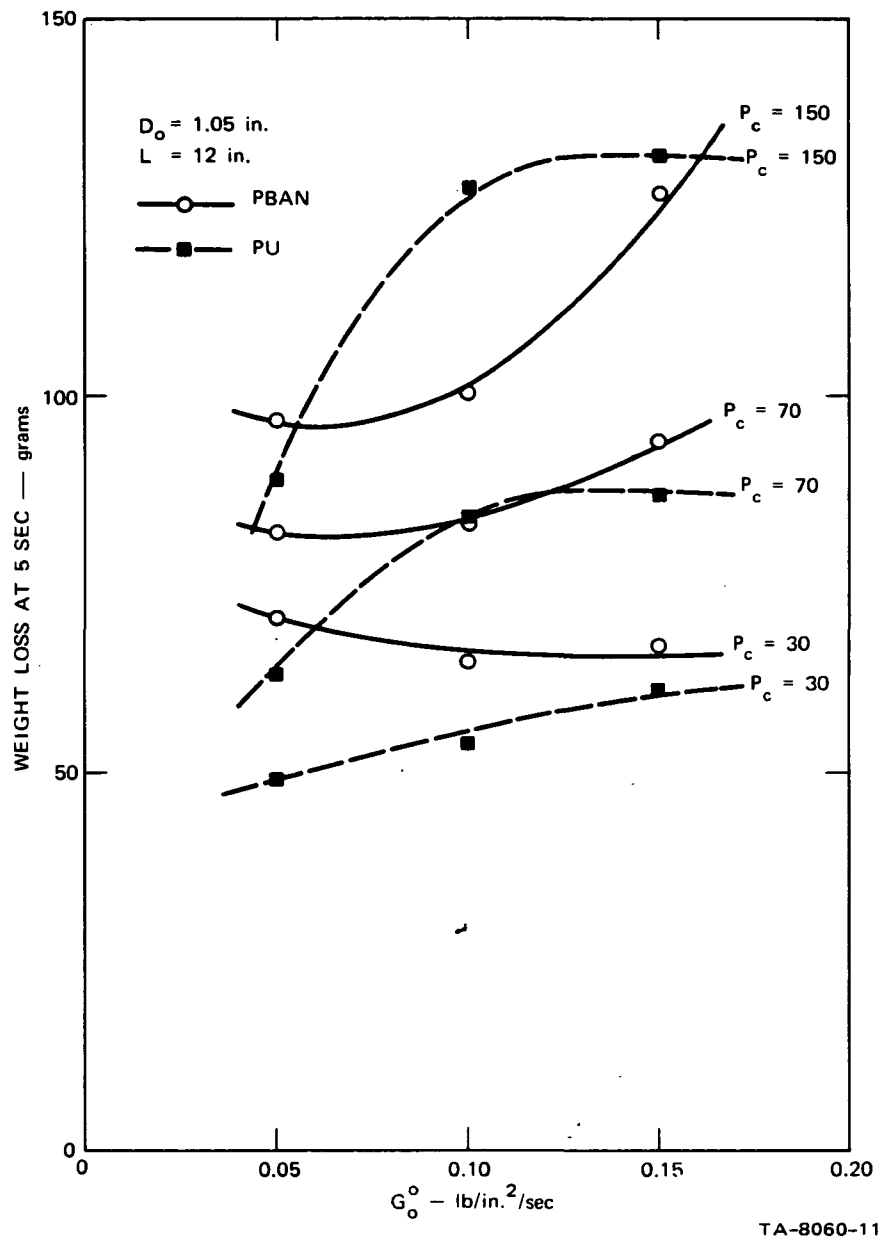
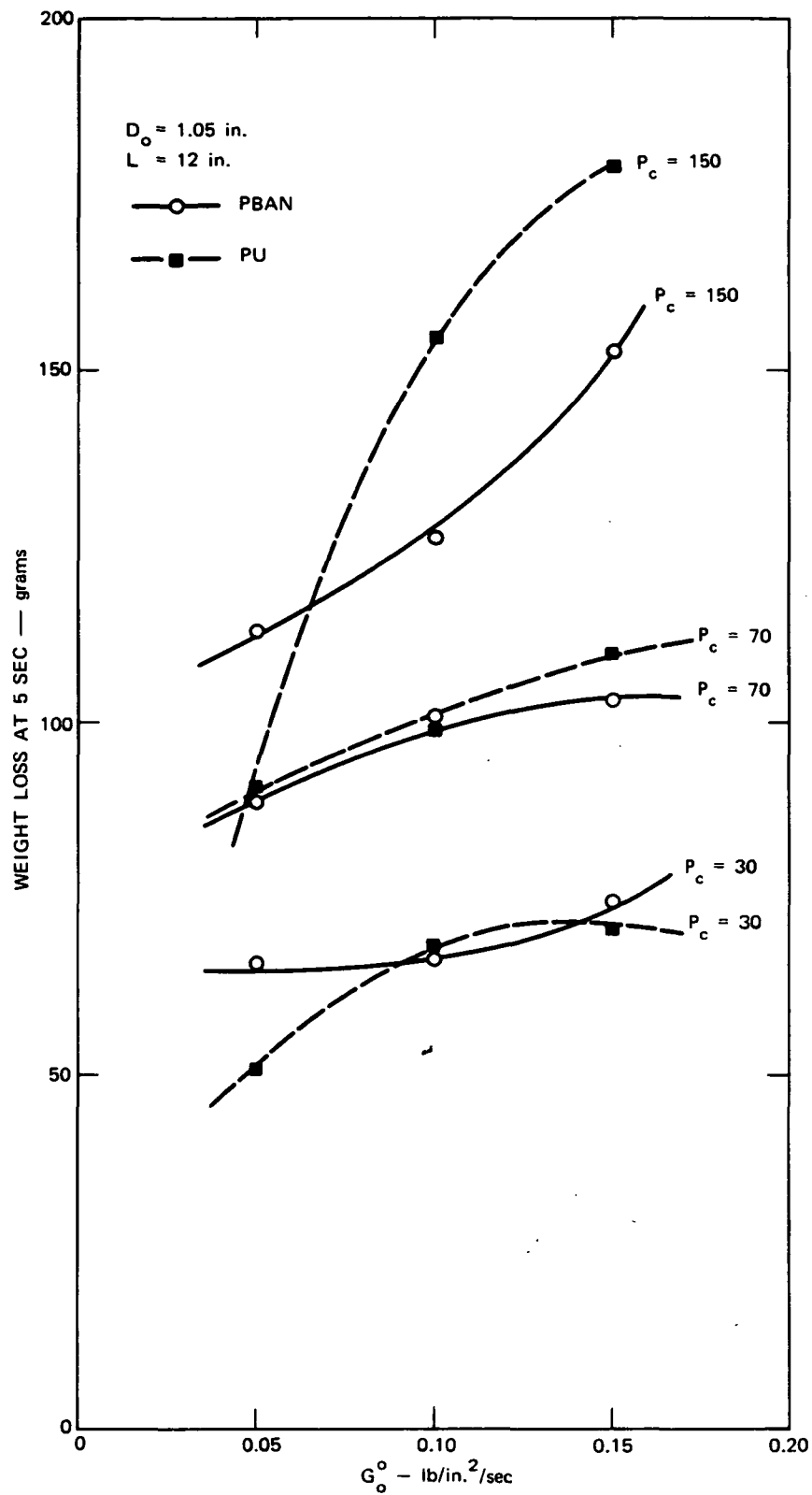


FIGURE 13 EXPERIMENTAL WEIGHT LOSS OF A HYBRID GRAIN CONTAINING 20 PERCENT ALUMINUM AS A FUNCTION OF OXIDIZER MASS FLUX



TA-8060-12

FIGURE 14 EXPERIMENTAL WEIGHT LOSS OF A HYBRID GRAIN CONTAINING 40 PERCENT ALUMINUM AS A FUNCTION OF OXIDIZER MASS FLUX

controlled regression rate to a diffusion-limited process is apparent.

As mentioned previously the PU system exhibits a different combustion mechanism than the PBAN system. As can be seen from the weight loss versus chamber pressure data which are also shown in Figs. 9 through 11, the PU system's regression rate is dependent upon chamber pressure for all of the values of oxidizer mass flux investigated. Since this system melts rather than chars, the velocity effect at constant oxidizer mass flux is absent. However, the influence of velocity is noticeable at low chamber pressures and high oxidizer mass flux. This is thought to be an erosion effect which is diminished by the addition of the aluminum. The aluminum not only increases the viscosity of the melted surface layer but also reduces the thermal profile thickness by increasing the regression rate.

C. Comparison with Calculated Weight Loss Behavior

A comparison between Figs. 1 through 3 and Figs. 9 through 11 shows that the qualitative behavior of weight loss as a function of chamber pressure is in best agreement with the calculated behavior at the highest oxidizer mass flux. At the lowest value of mass flux the PBAN curves tend to droop at high pressure, presumably because the velocity is too low to remove the char layer, and the PU curves tend to rise at low pressure, presumably because of erosive effects on the melted binder surface at low pressure. This behavior is also reflected in a comparison of Figs. 4 through 6 with Figs. 12 through 14.

In all cases the measured weight loss is larger than the predicted value. The reason for this discrepancy was not known at the time work was halted on the contract.

IV. CONCLUDING REMARKS

A simple analysis to describe the transition of hybrid rocket combustion from the diffusion-limited region at high pressure to the kinetic limited domain at low pressure has been developed. Good qualitative agreement has been obtained with measured regression rate behavior in those operating regimes where surface effects such as excessive melting or charring do not occur.

It remains to be seen whether the simple model can describe instability behavior in the pressure-sensitive regime. Future investigations of hybrid combustion phenomena should be directed toward an understanding of this regime of operation.

Appendix

COMPUTER CODE FOR CALCULATION OF HYBRID REGRESSION RATES

	PROGRAM HYBRID(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)	001
000003	REAL L,K,K1,K2,K3,K4,K5,K8,K9,M,M0,M1,M2,M3,N(100),NN,MN	002
000003	DIMENSION D(100),DATE(12),FUEL(12),OXID(12)	003
C	THIS PROGRAM IS BASED UPON HEAT-TRANSFER LIMITED HYBRID THEORY.	004
C	IT CALCULATES THE REGRESSION BEHAVIOR OF A CIRCULAR TUBE FUEL	005
C	GRAIN. THE INPUTS WHICH ARE NECESSARY FOR OPERATION OF THE	006
C	PROGRAM ARE DEFINED AS FOLLOWS:	007
C	D0 IS INITIAL INNER DIAMETER (IN.)	008
C	L IS LENGTH (IN.)	009
C	D2 IS OUTER DIAMETER (IN.)	010
C	K IS MASS FRACTION OF NON-VOLATILE SURFACE MATERIAL	011
C	K1 IS MASS FRACTION OF VOLATILE SURFACE MATERIAL WHICH FORMS	012
C	PARTICULATE COMBUSTION PRODUCTS	013
C	K2 IS TOTAL DENSITY OF FUEL GRAIN (LB/IN**3)	014
C	K3 IS EFFECTIVE HEAT OF GASIFICATION (BTU/LB)	015
C	M0 IS OXIDIZER FLOW RATE (LB/SEC)	016
C	(IF M0 VARIES, IT MAY EITHER BE HEAD AS DATA OR	017
C	DESCRIBED BY AN EQUATION.)	018
C	P0 IS CHAMBER PRESSURE (PSIA) (SEE THE ABOVE)	019
C	J IS CASE NUMBER	020
C	J=1 IF PARTICLES IN THE GRAIN PRODUCE PARTICULATE	021
C	COMBUSTION PRODUCTS	022
C	J=2 IF PARTICLES IN THE GRAIN PRODUCE GASEOUS	023
C	COMBUSTION PRODUCTS	024
C	J=3 IF A COMPLETELY VOLATILE GRAIN PRODUCES PARTICULATE	025
C	COMBUSTION PRODUCTS	026
C	U0 IS OXIDIZER TEMP. AT INLET (DEG RANKINE)	027
C	U5 IS COMBUSTION TEMP. AT AN O/F RATIO WHICH IS 3/4 OF THE	028
C	STOICHIOMETRIC VALUE AT 5 ATM. PRESSURE (DEG RANKINE)	029
C	C7 IS GAS-PHASE RADIATION CONSTANT	030
C	K4 IS MASS OF OXIDIZER CONSUMED PER UNIT MASS OF NON-VOLATILE	031
C	SURFACE MATERIAL IN PRODUCING PARTICULATE COMBUSTION PRODUCTS	032
C	K5 IS MASS OF OXIDIZER CONSUMED PER UNIT MASS OF VOLATILE	033
C	SURFACE MATERIAL IN PRODUCING PARTICULATE COMBUSTION PRODUCTS	034
C	C8 IS MASS OF PARTICULATE COMBUSTION PRODUCTS FORMED PER UNIT	035
C	MASS OF NON-VOLATILE SURFACE MATERIAL	036
C	E2 IS EMISSIVITY (ABSORPTIVITY) OF FUEL SURFACE	037
C	B IS MASS TRANSFER NUMBER	038
C	K8 IS DENSITY OF PARTICULATE COMBUSTION PRODUCTS (LB/IN**3)	039
C	C2 IS BOUNDARY LAYER DENSITY CORRECTION FACTOR	040
C	S IS OXIDIZER VISCOSITY AT TEMP. U0 (LB/IN-SEC)	041
C	T1 IS TIME INCREMENT FOR CALCULATIONS (SEC)	042
C	T2 IS QUIT TIME (SEC)	043
C	T3 IS TIME INCREMENT FOR PRINTOUT (SEC)	044
C	X1 IS DISTANCE INCREMENT FOR CALCULATIONS (X/L)	045
C	C9 IS THE RADIATION TEMPERATURE CONSTANT	
C	R6 IS THE PARTICLE RADIUS IN MICRONS	
000003	READ(5,1000) (DATE(I),I=1,12)	046
000015	1000 FORMAT(12A6)	047
000015	10 READ(5,1010) D0,L,D2,K,K1,K2,K3,K4,K5,C8,C9,T1,T2,T3,	048
	1 M0,P0,U0,U5,E2,B,K8,R6,QF	049
000077	IF(D0.EQ.0.0)GO TO 850	050
000100	1010 FORMAT(7F10.4)	051
000100	READ(5,1020) J	052
000106	1020 FORMAT(I1)	053
000106	READ(5,1000) (FUEL(I),I=1,12)	054
000120	READ(5,1000) (OXID(I),I=1,12)	055

000132	E3=0.0	056
000133	U2=U5*(1.0+3.33E-4*(P0-75.0))	057
000140	C7=0.003	059
000141	CP=0.4	
000143	NN=2.0	
000144	EF=27000.0	
000146	RR=0.75	
000147	TER=2.0	
000151	3000 TEX=2.0*TER-RR**2*TER**2+2.0*EXP(-TER)	
000162	IF(TEX.LT.2.01)GO TO 3020	
000165	TEM=TEM+0.01	
000167	GO TO 3000	
000167	3010 TER=TER+0.01	
000171	GO TO 3000	
000172	3020 IF(TEX.LT.1.99)GO TO 3010	
000175	WRITE(6,2070)TER	
000202	MR=0.0433	
000203	AR=0.8659	
000205	PR=150.0	
000206	UWR=1440.0	
000210	UFH=U5*(1.0+3.33E-4*(PR-75.0))	
000215	E1=3.307E-15	040
000216	C6=(3.0*16.387E12)/(4.0*K8*R6**3)	
000222	J1=1	043
000223	C1=0.036	044
000225	C2=1.0	045
000226	S=3.00E-6	046
000230	C3=(S/L)**0.2	047
000234	C5=3.14159	048
000235	C4=C5/4.0	049
000237	X1=0.02	070
000240	I4=INT(0.1/X1+0.5)	
000244	W=0.0	072
000244	U1=C9*U2	073
000247	WRITE(6,8888)	074
000252	8888 FORMAT(1H1)	075
000252	WRITE(6,2000) (DATE(I),I=1,12)	076
000264	2000 FORMAT(1H ,50X,12A6/)	077
000264	WRITE(6,2010) (FUEL(I),I=1,12),(OXID(I),I=1,12)	078
000304	2010 FORMAT(50H REGRESSION BEHAVIOR OF A CIRCULAR TUBE FUEL GRAIN//	079
	16H FUEL=,12A6/10H OXIDIZER=,12A6/)	080
000304	WRITE(6,2020) D0,L,K2,K3,B,P0,M0,U0,U2,U1,C7,E2,K,K1,K4,K5,C8	081
000352	WRITE(6,2021) T1,X1,T3,T2,J	082
000370	2020 FORMAT(19H INITIAL CONDITIONS//15H DIAMETER =,E14.5/	083
	1 15H LENGTH =,E14.5/15H DENSITY =,E14.5/	084
	2 15H EFF. H-SUB-V =,E14.5/15H BEE =,E14.5/	085
	3 15H PRESSURE =,E14.5/15H OXID. FLOW =,E14.5/	086
	4 15H INLET TEMP. =,E14.5/15H FLAME TEMP. =,E14.5/	087
	5 15H RAD. TEMP. =,E14.5/15H GAS CONST. =,E14.5/	088
	6 15H WALL ABSORPT.=,E14.5/15H METAL PCT. =,E14.5/	089
	7 15H PART. PCT. =,E14.5/15H ZETA =,E14.5/	090
	8 15H ZETA-1 =,E14.5/15H LAMBDA =,E14.5/	091
000370	2021 FORMAT(15H DEL-T =,E14.5/15H DEL-X/L =,E14.5/	
	1 15H PRINT TIME =,E14.5/15H QUIT TIME =,E14.5/	
	2 15H CASE =,I4)	
000370	WRITE(6,8888)	092
000374	WRITE(6,2000) (DATE(I),I=1,12)	093
000406	Q6=C1*C2*C3*(B)**0.23	094

000414	T4=0.0	005
000415	T5=0.0	
000416	T=0.0	006
000420	155 X=X1	007
000421	I=1	008
000422	I1=I4	009
000424	M=M0	100
000426	165 IF(T.GT.0.0)GO TO 175	101
000431	D(I)=D0	102
000433	175 R3=(X*L)/(5.0*D(I))	103
000437	IF(R3.LE.1.0)GO TO 190	104
000442	IF(R3.GT.5.0)GO TO 200	105
000445	IF(R3.GT.1.0)GO TO 210	106
000447	190 E=D(I)*(1.0-0.21*(R3)**0.8)	107
000456	U=U0	108
000460	GO TO 220	109
000461	200 E=D(I)*(1.0-0.21)	110
000464	U=U2	111
000466	GO TO 220	112
000467	210 E=D(I)*(1.0-0.21)	113
000472	U=U0+((U2-U0)/4.0)*(R3-1.0)	114
000501	220 A=C4*(E)**2	115
000503	Q1=C6*(X)**(-0.2)*(M/A)**0.8	116
000515	Q3=C5*Q1*D0*X1*L	117
000522	R1=Q1/(K2*(1.0-K))	118
000526	GO TO (255,345,300),J	119
000535	255 IF(I.GT.1)GO TO 280	120
000541	M=M0*(1.0-K*K4/(1.0-K))*Q3	121
000550	M1=M0+Q3*1.0/(1.0-K)	122
000555	Q5=Q3	123
000556	N(I)=C6*C8*K/(1.0-K)*P0/U*1.0/M*Q3*(R3)**(-0.8)	124
000574	GO TO 366	125
000575	280 M=M*(1.0-K*K4/(1.0-K))*Q4	126
000604	M1=M1+Q4*1.0/(1.0-K)	127
000612	IF(R3.GT.1.0)GO TO 295	128
000615	N(I)=C6*C8*K/(1.0-K)*P0/U*1.0/M*Q5*(R3)**(-0.8)	129
000633	GO TO 366	130
000634	295 N(I)=C6*C8*K/(1.0-K)*P0/U*1.0/M*Q5	131
000646	GO TO 366	132
000646	300 IF(I.GT.1)GO TO 325	133
000652	M=M0*(1.0-K1-K1*K5)*Q3	134
000657	M1=M0+Q3	135
000660	Q5=Q3	136
000661	N(I)=C6*K1*P0/U*1.0/M*Q3*(R3)**(-0.8)	137
000674	GO TO 366	138
000675	325 M=M*(1.0-K1-K1*K5)*Q4	139
000702	M1=M1+Q4	140
000704	IF(R3.GT.1.0)GO TO 340	141
000707	N(I)=C6*K1*P0/U*1.0/M*Q5*(R3)**(-0.8)	142
000721	GO TO 366	143
000722	340 N(I)=C6*K1*P0/U*1.0/M*Q5	144
000731	GO TO 366	145
000731	345 IF(I.GT.1)GO TO 360	146
000735	M=M0*(1.0/(1.0-K))*Q3	147
000741	M1=M	148
000742	N(I)=C7*P0	149
000745	GO TO 366	150
000746	360 M=M*(1.0/(1.0-K))*Q4	151

000752	M1=M	152
000753	N(I)=C7*P0	153
000756	366 IF(J1.EQ.2)GO TO 371	154
000760	R2=R1	155
000761	UW=UWR/(1.0-UWR*ALOG(10.0*R2)/EF)	
000771	TEE=TER*(M/MR*AR/A*(PR/P0)**NN*(UFR/U2)**(NN*2.0)*(1.0-CP*(UFR-UWR 1)/QF)/(1.0-CP*(U2-UW)/QF)*EXP(-UFR/U2))	
001032	R2=R2*((2.0/TEE)**0.5*(1.0-1.0/TEE*(1.0-EXP(-TEE)))*0.5)	
001051	GO TO 390	156
001052	371 IF(J.EQ.2)GO TO 384	157
001054	IF(N(I).GT.0.0)GO TO 375	158
001057	R2=R1	159
001057	UW=UWR/(1.0-UWR*ALOG(10.0*R2)/EF)	
001067	TEE=TER*(M/MR*AR/A*(PR/P0)**NN*(UFR/U2)**(NN*2.0)*(1.0-CP*(UFR-UWR 1)/QF)/(1.0-CP*(U2-UW)/QF)*EXP(-UFR/U2))	
001130	R2=R2*((2.0/TEE)**0.5*(1.0-1.0/TEE*(1.0-EXP(-TEE)))*0.5)	
001147	GO TO 390	160
001150	375 IF(I.LT.I4)GO TO 382	
001153	IF(I.GT.(8*I4))GO TO 382	
001156	IF(I.EQ.I1)GO TO 382	163
001157	GO TO 387	164
001157	382 IF(T.EQ.T5)GO TO 590	
001161	GO TO 387	166
001162	384 IF(I.GT.(2*I4))GO TO 387	
001166	GO TO 375	168
001166	387 Q2=E1*E2/K3*E3*(U1)**4	170
001173	R2=Q1*(Q2/Q1*EXP(-Q2/Q1))/(K2*(1.0-K))	171
001206	UW=UWR/(1.0-UWR*ALOG(10.0*R2)/EF)	
001215	TEE=TER*(M/MR*AR/A*(PR/P0)**NN*(UFR/U2)**(NN*2.0)*(1.0-CP*(UFR-UWR 1)/QF)/(1.0-CP*(U2-UW)/QF)*EXP(-UFR/U2))	
001256	R2=R2*((2.0/TEE)**0.5*(1.0-1.0/TEE*(1.0-EXP(-TEE)))*0.5)	
001275	390 Q4=C5*K2*(1.0-K)*R2*D(I)*X1*L	172
001305	Q5=Q5+Q4	173
001306	IF(I.EQ.I1)GO TO 495	174
001311	D(I)=D(I)+2.0*R2*T1	175
001314	IF(D(I).GT.0.2)GO TO 795	176
001320	405 IF(X.GT.0.995)GO TO 425	177
001324	I=I+1	178
001325	X=X*X1	179
001327	GO TO 165	180
001327	425 IF(T.EQ.0.0)GO TO 450	181
001330	M3=(M1*M2)/2.0-M0	182
001334	W=W+M3*T1	183
001336	M2=M1	184
001337	IF(T.EQ.T4)GO TO 455	185
001342	T=T+T1	186
001342	IF(T.GT.T2)GO TO 800	187
001346	GO TO 155	188
001346	450 M2=M1	189
001347	IF(J1.EQ.2)GO TO 455	190
001352	J1=2	191
001353	GO TO 155	192
001353	455 WRITE(6,2030)	193
001357	2030 FORMAT(/13H AVG. DEL-R,6X,8HWT. LOSS,6X,8HMGAS FLOW,5X, 1 10HMTOTAL FLOW,7X,3HG-0)	194
001357	WRITE(6,2035)	195
001363	2035 FORMAT(10H (IN),11X,4H(GH),8X,8H(LB/SEC),6X,8H(LB/SEC), 1 3X,12H(LB/IN2-SEC))	

001363	D6=(W/(C4*K2*L))*(D0)**2)**0.5	196
001373	AVGD=(D6-D0)/2.0	197
001376	WTL=W*453.6	198
001400	GSUB0=W0/(C4*(D6)**2)	199
001404	WRITE(6,2040) AVGD,WTL,M,M1,GSUB0	200
001421	2040 FORMAT(5E14,5//)	201
001421	T=T+T1	202
001423	T4=T4+T3	203
001425	IF(T.GT.T2)GO TO 800	204
001430	GO TO 155	205
001430	495 IF(T.EQ.T4)GO TO 506	206
001432	D(I)=D(I)+2.0*R2*T1	207
001437	I1=I1+I4	208
001441	GO TO 405	209
001441	506 IF(J1.EQ.2)GO TO 510	210
001443	GO TO 405	211
001444	510 IF(I1.EQ.I4)GO TO 520	212
001446	GO TO 535	213
001447	520 WRITE(6,2050) T	214
001455	2050 FORMAT(/11M TIME/F10.0//)	215
001455	WRITE(6,2055)	
001461	2055 FORMAT(25M TOTAL,7X,10MCONVECTIVE)	
001461	WRITE(6,2060)	216
001465	2060 FORMAT(13M DISTANCE,5X,8MREG RATE,6X,8MREG RATE,8X,	217
	1 SMDL-R,7X,9MTUBE AREA,5X,9MFLOW AREA,5X,10MEMISSIVITY)	218
001465	WRITE(6,2065)	
001471	2065 FORMAT(11M (X/L),7X,8M(IN/SEC),6X,8M(IN/SEC),8X,4M(IN),	
	1 9X,7M(IN**2),7X,7M(IN**2)//)	
001471	535 DELR=(D(I)-D0)/2.0	219
001474	TUBEAC=C4*(D(I))**2	220
001477	FLOWAC=C4*(E)**2	221
001501	WRITE(6,2070) X,R2,R1,DELR,TUBEAC,FLOWAC,E3	222
001522	2070 FORMAT(7E14,5)	223
001522	D(I)=D(I)+2.0*R2*T1	224
001527	IF(D(I).GT.D2)GO TO 795	225
001533	I1=I1+I4	226
001534	GO TO 405	227
001535	590 T5=T5+(2.0*T3)	
001540	600 R=U(I)/2.0	228
001542	R0=R-0.25	229
001544	Y1=3.14159/30.0	230
001545	Y2=ATAN(1.0/((R*R)/(R0*R0)-1.0)**0.5)	231
001556	E3=0.0	232
001557	J5=1	233
001561	633 K9=1.0	234
001562	Y=Y1/100.0	235
001565	635 Z=3.14159/2.0	236
001566	J4=1	237
001570	645 Y3=2.0*R*COS(Y)	238
001574	IF(Y.GT.Y2)GO TO 650	239
001600	S3=(Y3/2.0-(R0*R0-R*R*(SIN(Y))**2)**0.5)/SIN(Z)	240
001614	650 X3=J4*X1*L	241
001617	S4=Y3/SIN(Z)	242
001622	IF(Y.LT.Y2)GO TO 666	243
001625	K9=0.0	244
001626	S3=0.0	245
001627	666 IF(J5.EQ.1)GO TO 670	246
001631	S5=K9*EXP(-N(I-J4)*S3)-K9*EXP(-N(I-J4)*(S4-S3))*EXP(-N(I-J4)*S4)	247

001656	GO TO 675	248
001657	670 S5=K9*EXP(-N(I+J4)*S3)-K9*EXP(-N(I+J4)*(S4-S3))*EXP(-N(I+J4)*S4)	249
001704	675 S6=(1.0-S5)*(SIN(Z))*2*COS(Y)	250
001714	Z1=(Y3*X1*L)/((X3)**2*(Y3)**2)	251
001721	S7=S6*Z1*Y1*2.0/3.14159	252
001724	E3=E3+S7/1.06988	253
001727	Z=Z-Z1	254
001731	J4=J4+1	255
001733	IF(J5.EQ.1)GO TO 705	256
001735	IF(J4.GT.I)GO TO 720	257
001740	IF(J4.GT.10)GO TO 720	258
001742	GO TO 645	259
001742	705 IF(J4.GT.(1.0/X1-I))GO TO 720	260
001751	IF(J4.GT.10)GO TO 720	261
001754	GO TO 645	262
001754	720 Y=Y+Y1	263
001756	IF(Y.GT.(3.14159/2.0))GO TO 745	264
001761	GO TO 635	265
001761	745 IF(J5.EQ.2)GO TO 750	266
001763	J5=2	267
001764	GO TO 633	268
001765	750 GO TO 387	269
001766	795 WRITE(6,2080)	270
001772	2080 FORMAT(/37H SPECIFIED EXTERNAL DIAMETER EXCEEDED/)	271
001772	800 GO TO 10	272
001773	850 STOP	273
001775	END	274

MAR 4 1970

REGRESSION BEHAVIOR OF A CIRCULAR TUBE FUEL GRAIN

FUEL=PU

OXIDIZER=OXYGEN

INITIAL CONDITIONS

DIAMETER	=	1.05000E+00
LENGTH	=	1.20000E+01
DENSITY	=	4.27014E-02
EFF. H-SUB-V	=	6.30000E+02
H _{EE}	=	9.10000E+00
PRESSURE	=	5.00000E+01
OXID. FLOW	=	4.33000E-02
INLET TEMP.	=	5.40000E+02
FLAME TEMP.	=	6.11863E+03
RAD. TEMP.	=	3.59164E+03
GAS CONST.	=	3.00000E-03
WALL ABSORPT.	=	9.00000E-01
METAL PCT.	=	2.00000E-01
PART. PCT.	=	0.
ZETA	=	8.88000E-01
ZETA-1	=	0.
LAMBDA	=	1.88800E+00
DEL-T	=	2.50000E-01
UEL-X/L	=	2.00000E-02
PRINT TIME	=	1.00000E+00
QUIT TIME	=	5.00000E+00
CASE	=	1

MAR 4 1970

TIME 0						
DISTANCE (X/L)	TOTAL REG RATE (IN/SEC)	CONVECTIVE REG RATE (IN/SEC)	DEL-R (IN)	TUBE AREA (IN**2)	FLOW AREA (IN**2)	EMISSIVITY
1.00000E-01	7.91429E-03	1.36723E-02	0.	8.65901E-01	7.57831E-01	4.98394E-01
2.00000E-01	7.31592E-03	1.31353E-02	0.	8.65901E-01	6.82387E-01	4.98394E-01
3.00000E-01	6.99811E-03	1.32913E-02	0.	8.65901E-01	6.17856E-01	4.98394E-01
4.00000E-01	6.78799E-03	1.37389E-02	0.	8.65901E-01	5.60467E-01	4.98394E-01
5.00000E-01	6.61644E-03	1.36930E-02	0.	8.65901E-01	5.40409E-01	4.98394E-01
6.00000E-01	6.47172E-03	1.33573E-02	0.	8.65901E-01	5.40409E-01	4.98394E-01
7.00000E-01	6.35357E-03	1.30982E-02	0.	8.65901E-01	5.40409E-01	4.98394E-01
8.00000E-01	6.25408E-03	1.28926E-02	0.	8.65901E-01	5.40409E-01	4.98394E-01
9.00000E-01	6.16832E-03	1.27264E-02	0.	8.65901E-01	5.40409E-01	4.98394E-01
1.00000E+00	6.09307E-03	1.25901E-02	0.	8.65901E-01	5.40409E-01	4.98394E-01
AVG. DEL-R (IN)	WT. LOSS (GM)	GAS FLOW (LB/SEC)	TOTAL FLOW (LB/SEC)	G-0 (LB/IN2-SEC)		
0.	0.	5.07208E-02	5.52229E-02	5.00057E-02		

TIME 1						
DISTANCE (X/L)	TOTAL REG RATE (IN/SEC)	CONVECTIVE REG RATE (IN/SEC)	DEL-R (IN)	TUBE AREA (IN**2)	FLOW AREA (IN**2)	EMISSIVITY
1.00000E-01	7.89751E-03	1.33308E-02	7.90782E-03	8.92182E-01	7.82113E-01	4.98394E-01
2.00000E-01	7.30639E-03	1.28209E-02	7.31220E-03	8.90189E-01	7.03482E-01	4.98394E-01
3.00000E-01	6.98960E-03	1.29764E-02	6.99478E-03	8.89128E-01	6.36888E-01	4.98394E-01
4.00000E-01	6.77832E-03	1.34122E-02	6.78423E-03	8.88424E-01	5.77905E-01	4.98394E-01
5.00000E-01	6.60929E-03	1.34291E-02	6.61367E-03	8.87854E-01	5.54110E-01	4.98394E-01
6.00000E-01	6.46648E-03	1.31072E-02	6.46967E-03	8.87374E-01	5.53810E-01	4.98394E-01
7.00000E-01	6.34976E-03	1.28590E-02	6.35207E-03	8.86981E-01	5.53565E-01	4.98394E-01
8.00000E-01	6.25137E-03	1.26624E-02	6.25299E-03	8.86650E-01	5.53358E-01	4.98394E-01
9.00000E-01	6.16648E-03	1.25037E-02	6.16757E-03	8.86365E-01	5.53180E-01	4.98394E-01
1.00000E+00	6.09193E-03	1.23738E-02	6.09258E-03	8.86115E-01	5.53024E-01	4.98394E-01
AVG. DEL-R (IN)	WT. LOSS (GM)	GAS FLOW (LB/SEC)	TOTAL FLOW (LB/SEC)	G-0 (LB/IN2-SEC)		
7.04133E-03	5.43491E+00	5.07943E-02	5.53410E-02	4.86909E-02		

TIME 2						
DISTANCE (X/L)	TOTAL REG RATE (IN/SEC)	CONVECTIVE REG RATE (IN/SEC)	DEL-R (IN)	TUBE AREA (IN**2)	FLOW AREA (IN**2)	EMISSIVITY
1.00000E-01	7.88208E-03	1.30037E-02	1.57997E-02	9.18803E-01	8.06732E-01	4.98272E-01
2.00000E-01	7.29792E-03	1.25190E-02	1.46156E-02	9.14784E-01	7.24877E-01	4.98272E-01
3.00000E-01	6.98210E-03	1.26739E-02	1.39817E-02	9.12636E-01	6.56194E-01	4.98272E-01
4.00000E-01	6.76970E-03	1.30985E-02	1.35594E-02	9.11206E-01	5.95594E-01	4.98272E-01
5.00000E-01	6.60260E-03	1.31740E-02	1.32206E-02	9.10060E-01	5.67969E-01	4.98272E-01
6.00000E-01	6.46161E-03	1.28652E-02	1.29345E-02	9.09093E-01	5.67365E-01	4.98272E-01
7.00000E-01	6.34626E-03	1.26274E-02	1.27007E-02	9.08303E-01	5.66872E-01	4.98272E-01
8.00000E-01	6.24891E-03	1.24393E-02	1.25036E-02	9.07637E-01	5.66456E-01	4.98272E-01
9.00000E-01	6.16484E-03	1.22878E-02	1.23336E-02	9.07063E-01	5.66098E-01	4.98272E-01
1.00000E+00	6.09093E-03	1.21641E-02	1.21843E-02	9.06559E-01	5.65784E-01	4.98272E-01
AVG. DEL-R (IN)	WT. LOSS (GM)	GAS FLOW (LB/SEC)	TOTAL FLOW (LB/SEC)	G-0 (LB/IN2-SEC)		
1.40594E-02	1.09239E+01	5.08687E-02	5.54605E-02	4.74313E-02		

TIME
3

DISTANCE (X/L)	TOTAL REG RATE (IN/SEC)	CONVECTIVE REG RATE (IN/SEC)	DEL-R (IN)	TUBE AREA (IN**2)	FLOW AREA (IN**2)	EMISSIONIVITY
1.00000E-01	7.86943E-03	1.26901E-02	2.36769E-02	9.45764E-01	8.31689E-01	4.98272E-01
2.00000E-01	7.29191E-03	1.22289E-02	2.19111E-02	9.39686E-01	7.46575E-01	4.98272E-01
3.00000E-01	6.97695E-03	1.23833E-02	2.09617E-02	9.36427E-01	6.75776E-01	4.98272E-01
4.00000E-01	6.76338E-03	1.27972E-02	2.03266E-02	9.34250E-01	6.13535E-01	4.98272E-01
5.00000E-01	6.59762E-03	1.29274E-02	1.98213E-02	9.32519E-01	5.81985E-01	4.98272E-01
6.00000E-01	6.45837E-03	1.26311E-02	1.93948E-02	9.31060E-01	5.81074E-01	4.98272E-01
7.00000E-01	6.34430E-03	1.24032E-02	1.90461E-02	9.29867E-01	5.80330E-01	4.98272E-01
8.00000E-01	6.24794E-03	1.22232E-02	1.87521E-02	9.28862E-01	5.79703E-01	4.98272E-01
9.00000E-01	6.16464E-03	1.20786E-02	1.84983E-02	9.27996E-01	5.79162E-01	4.98272E-01
1.00000E+00	6.09134E-03	1.19608E-02	1.82753E-02	9.27234E-01	5.78687E-01	4.98272E-01
AVG. DEL-R (IN)	WT. LOSS (GM)	GAS FLOW (LB/SEC)	TOTAL FLOW (LB/SEC)	G=0 (LB/IN2-SEC)		
2.10561E-02	1.64678E+01	5.09454E-02	5.55838E-02	4.62236E-02		

TIME
4

DISTANCE (X/L)	TOTAL REG RATE (IN/SEC)	CONVECTIVE REG RATE (IN/SEC)	DEL-R (IN)	TUBE AREA (IN**2)	FLOW AREA (IN**2)	EMISSIONIVITY
1.00000E-01	7.84975E-03	1.23890E-02	3.15421E-02	9.73073E-01	8.56991E-01	4.96936E-01
2.00000E-01	7.27890E-03	1.19497E-02	2.92012E-02	9.64905E-01	7.68581E-01	4.96936E-01
3.00000E-01	6.96521E-03	1.21032E-02	2.79372E-02	9.60508E-01	6.95638E-01	4.96936E-01
4.00000E-01	6.75102E-03	1.25068E-02	2.70881E-02	9.57561E-01	6.31733E-01	4.96936E-01
5.00000E-01	6.58635E-03	1.26879E-02	2.64173E-02	9.55235E-01	5.96162E-01	4.96936E-01
6.00000E-01	6.44872E-03	1.24033E-02	2.58522E-02	9.53278E-01	5.94941E-01	4.96936E-01
7.00000E-01	6.33586E-03	1.21847E-02	2.53900E-02	9.51679E-01	5.93943E-01	4.96936E-01
8.00000E-01	6.24042E-03	1.20125E-02	2.49999E-02	9.50331E-01	5.93101E-01	4.96936E-01
9.00000E-01	6.15785E-03	1.18742E-02	2.46631E-02	9.49167E-01	5.92375E-01	4.96936E-01
1.00000E+00	6.08514E-03	1.17620E-02	2.43671E-02	9.48145E-01	5.91737E-01	4.96936E-01
AVG. DEL-R (IN)	WT. LOSS (GM)	GAS FLOW (LB/SEC)	TOTAL FLOW (LB/SEC)	G=0 (LB/IN2-SEC)		
2.80333E-02	2.20674E+01	5.10153E-02	5.56961E-02	4.50646E-02		

TIME
5

DISTANCE (X/L)	TOTAL REG RATE (IN/SEC)	CONVECTIVE REG RATE (IN/SEC)	DEL-R (IN)	TUBE AREA (IN**2)	FLOW AREA (IN**2)	EMISSIONIVITY
1.00000E-01	7.84062E-03	1.21002E-02	3.93883E-02	1.00070E+00	8.82613E-01	4.96936E-01
2.00000E-01	7.27590E-03	1.16815E-02	3.64789E-02	9.90413E-01	7.90874E-01	4.96936E-01
3.00000E-01	6.96294E-03	1.18343E-02	3.49015E-02	9.84856E-01	7.15762E-01	4.96936E-01
4.00000E-01	6.74759E-03	1.22284E-02	3.38377E-02	9.81117E-01	6.50173E-01	4.96936E-01
5.00000E-01	6.58324E-03	1.24572E-02	3.30024E-02	9.78187E-01	6.10486E-01	4.96936E-01
6.00000E-01	6.44719E-03	1.21839E-02	3.23003E-02	9.75726E-01	6.08951E-01	4.96936E-01
7.00000E-01	6.33549E-03	1.19743E-02	3.17256E-02	9.73715E-01	6.07696E-01	4.96936E-01
8.00000E-01	6.24094E-03	1.18095E-02	3.12405E-02	9.72019E-01	6.06637E-01	4.96936E-01
9.00000E-01	6.15905E-03	1.16775E-02	3.08213E-02	9.70555E-01	6.05723E-01	4.96936E-01
1.00000E+00	6.08687E-03	1.15706E-02	3.04528E-02	9.69268E-01	6.04920E-01	4.96936E-01
AVG. DEL-R (IN)	WT. LOSS (GM)	GAS FLOW (LB/SEC)	TOTAL FLOW (LB/SEC)	G=0 (LB/IN2-SEC)		
3.49873E-02	2.77192E+01	5.10949E-02	5.58239E-02	4.39523E-02		

REFERENCES

1. Marxman, G. A., Wooldridge, C. E., and Muzzy, R. J., "Fundamentals of Hybrid Boundary Layer Combustion," Heterogeneous Combustion, Progress in Astronautics and Aeronautics, Vol. 15, Academic Press, New York, 1964, p. 485.
2. Marxman, G. A., and Gilbert, M., "Turbulent Boundary Layer Combustion in the Hybrid Rocket," Ninth Symposium (International) on Combustion, Academic Press, New York, 1963, p. 371.
3. Barrere, M., and Moutet, A., "La Propulsion par Fusees Hybrides," presented at the International Astronautical Congress, Paris, September 1963.
4. Green, L., Jr., "Introductory Considerations of Hybrid Rocket Combustion," Heterogeneous Combustion, Progress in Astronautics and Aeronautics, Vol. 15, Academic Press, New York, 1964, p. 451.
5. Marxman, G. A., and Wooldridge, C. E., "Research on the Combustion Mechanism of Hybrid Rockets," presented at the Combustion and Propulsion Panel, AGARD, NATO, San Diego, California, April 22-24, 1965.
6. Marxman, G. A., "Combustion in the Turbulent Boundary Layer on a Vaporizing Surface," Tenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1965, p. 1337.
7. Wooldridge, C. E., Marxman, G. A., and Kier, R. J., "Investigation of Combustion Instability in Hybrid Rockets", Final Report, NASA Contract NAS 1-7310, Stanford Research Institute, September 1969.
8. Smoot, L. D., and Price, C. F., "Regression Rate Mechanism of Non-metalized Hybrid Fuel Systems," AIAA J. 3, 1408-1413 (1965).
9. _____, "Regression Rates of Metalized Hybrid Fuel Systems," AIAA J. 4, 910-915 (1966).
10. _____, "Pressure Dependence of Hybrid Fuel Regression Rates," AIAA J. 5, 102-106 (1967).